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ABSTRACT
        This document is the Interim Report on future directions for
Federal support of research and development in high performance computing,
communications, information technology, and the Next Generation Internet.
This report provides a more detailed explanation of the findings and
recommendations summarized by the President's Information Technology Advisory
Committee (PITAC) on June 3, 1998. The report is divided into five main
sections. The first section identifies and discusses 10 critical information
technology transformations that will enable identification of common
information technology challenges critical to the Nation's future and provide
a framework for PITAC's recommendations for Federal research investments.
These transformations will affect how citizens: communicate; store and access
information; become healthier and receive proper medical care; learn; conduct
business; work; design and build things; conduct research; sustain a livable
environment; and manage government in the next millennium. The second section
focuses on setting Federal R&D priorities and presents these findings,
followed by recommendations: total Federal information technology R&D
investment is inadequate; and Federal information technology R&D is
excessively focused on near-term problems. Four areas of overall research
agenda particularly need attention and must be a major part of a strategic
initiative in long-term R&D: software, scalable information infrastructure,
high end computing, and socioeconomic and workforce impacts. These areas are
detailed in the third section, with findings and recommendations provided for
each area. The fourth section focuses on support and implementation of new
Federal research initiatives and presents recommendations for new and diverse
modes of funding. The fifth section focuses on creating an effective
management structure for new Federal research initiatives, and discusses
managing long-term research; coordinating long-term research; and the review
process. A sixth section presents the conclusion. (AEF)

ED 462 974

PRESIDENT'S INFORMATION TECHNOLOGY ADVISORY COMMITTEE

INTERIM REPORT TO THE PRESIDENT

August 1998

National Coordination Office for Computing,
Information, and Communications
4201 Wilson Boulevard, Suite 690
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2

President's Information Technology Advisory Committee

August 10, 1998

The President of the United States
The White House

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Dear Mr. President:

We are pleased to present our Interim Report on future directions for Federal support of research and development in high performance computing, communications, information technology, and the Next Generation Internet.

This report provides a more detailed explanation of the findings and recommendations summarized in our letter dated June 3, 1998. We were very encouraged to hear you address our concern about the adequacy of Federal support for long-term information technology research and development in public remarks you made shortly after receiving that letter. At that time, you indicated that your budget for the year 2000 will contain significant increases in computing and communications research, and called upon Dr. Neal Lane, your new Advisor for Science and Technology, to develop a detailed plan in cooperation with the research community. We believe that the report we are submitting today will establish the initial parameters for that plan and the priorities needed to guide Federal support for information technology research and development in the 21st Century.

Our nation's leadership in development and use of advanced information technology contributes in large measure to our global competitiveness, national security, and quality of life. Today, we are reaping the benefits of technical advancements paved by past Federal investments to support research in information technology. Our future ability to harness the power and promise of this technology depends upon our willingness to maintain an adequate research base. The Committee values your support in ensuring that the Nation gives priority to making the critical investments needed to support that base.

Respectfully,

Bill Joy
Co-Chairman

Ken Kennedy
Co-Chairman

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Table of Contents

Table of Contents

Executive Summary

Information technology (IT) will be one of the key factors driving progress in the 21st century—it is quite literally transforming the way we live, learn, work, and play. Advances in computing and communications technology will create a new infrastructure for business, scientific research and social interaction. That infrastructure will provide us with new tools for communicating throughout the world, and for acquiring knowledge and insight from information. Information technology will help us to understand our effect on the natural environment, and to protect it. It will provide a vehicle for economic growth. Information technology can make the workplace more rewarding, improve the quality of health care, and make government itself more responsive and accessible to the needs of its citizens.

Vigorous information technology research and development (R&D) is essential for achieving America's 21st century aspirations. The technical advances that led to today's information tools, such as electronic computers and the Internet, began with Federal government support of research in partnership with industry and universities. All of these innovations depended on patient investment in fundamental and applied research.

We have had a spectacular return on that Federal government research investment. Businesses that produce computers, semiconductors, software, and communications equipment have accounted for one-third the total growth in U.S. production since 1992, creating millions of high paying new jobs. As we approach the 21st century, the opportunities for innovation in IT are larger than they have ever been—and more important. We have an essential national interest in ensuring a continued flow of good new ideas in IT.

After careful review of the Federal programs, however, this Committee has concluded that Federal support for research in information technology is dangerously inadequate. Research

programs intended to maintain the flow of new ideas in IT are turning away large numbers of excellent proposals. In addition, current support is taking a short-term focus, looking for immediate returns, rather than investigating high-risk long-term technologies. Significant new research on computers and communication systems serves our needs while protecting us from catastrophic failures of the complex systems that now underpin our transportation, defense, business, finance, and healthcare infrastructure. The current Federal program is inadequate to start necessary new centers and research programs. Computers on university campuses and other civilian research facilities are falling rapidly behind the state of the art. The end result is that critical problems are going unsolved and we are endangering the flow of ideas that have fueled the information economy.

Ideally there should be a lead agency with responsibility to organize an IT R&D program appropriate for the 21st century. Much of the IT research sponsored by the Federal government is conducted by agencies in which IT research is only an accessory to the agency's primary mission, be it space exploration, medicine or weapons design. When budgets become tight, it is natural for such agencies to focus on activities that directly support their mission to the detriment of long-term, fundamental research.

To address these problems, the Federal budget for the year 2000 should include a commitment to sustained growth in IT research, along with a new management system designed to foster innovative research. The Federal IT research program must include vigorous support for fundamental and applied research and must ensure that the U.S. research community is equipped with state-of-the art facilities.

The FY 2000 budget must also ensure that advances in IT work to benefit all Americans, and that all Americans have the education and training needed to prosper in a world that will be increasingly dominated by dependence on information technology.

I. Principal Conclusions

Federal information technology R&D investment is inadequate.
Measured in constant (non-inflated) dollars, support in most critical areas has been flat or declining for nearly a decade, while the importance of IT to our economy has increased dramatically. As a result, the Nation is gravely under-investing in the long-term, high-risk research that can replenish the reservoir of ideas that will lead to innovations in IT in generations to come. IT R&D investment should increase by roughly a billion dollars over the next five years with emphasis placed on support for fundamental research.

Federal IT R&D is too heavily focused on near-term problems.
Much of the Federal investment in IT R&D is being handled by

2

mission agencies. In the face of the enormous increases in information technology problems to be addressed, funding agencies have had to prioritize their investments. Inevitably, priority has been given to short-term mission-oriented goals over long-term research. This reflects the situation in the private sector as well. As a result, investment in long-term high-risk research has been curtailed. This trend threatens to interrupt the flow of ideas that has driven the information economy in this decade and threatens efforts to solve nationally important problems.

II. Research Priorities

Four areas of the overall research agenda particularly need attention, and must be a major part of a strategic initiative in long-term research and development:

1. **Software** – The demand for software has grown far faster than the resources we have to produce it. The result is that desperately needed software is not being developed. Furthermore, the nation needs software that is far more usable, reliable, and powerful than what is being produced today. We have become dangerously dependent on large software systems whose behavior is not well understood and which often fail in unpredicted ways. Therefore, increases in research on software should be given the highest priority. Special emphasis should be placed on component based software design and production techniques and techniques for designing and testing reliable, fault-tolerant systems. Specifically, the Federal program should:

   ■ Fund more fundamental research in software development methods and component technologies.

   ■ Sponsor a national library of software components. Aggressively address the technical barriers that have inhibited earlier efforts.

   ■ Make software research a substantive component of every major IT research initiative.

   ■ Support fundamental research in human-computer interfaces and interaction.

2. **Scalable Information Infrastructure** – The tools now used to operate an Internet with 30 million computers cannot be safely extended to networks that will involve billions of distinct components. Significant research is needed to understand the behavior of complex systems serving diverse customers while achieving flexibility and scalability. Expanded programs are needed to design systems which will include large numbers of users, users demanding high reliability and low latency, and

mobile users requiring rapid reconfiguration of networks. To meet these needs, the Federal program should:

■ Increase funding for research and development on core software and communications technologies aimed directly at the challenge of scaling the information infrastructure.

■ Continue expansion of the Next Generation Internet testbeds, including industry access and partnerships in order to foster the rapid commercialization and deployment of enabling technologies.

3. **High-End Computing** – Extremely fast computing systems, with both rapid calculation and rapid data movement, are essential to provide accurate weather and climate forecasting, to support advanced manufacturing design, to design new pharmaceuticals, to conduct scientific research in a variety of different areas, and to support critical national interests. Although they achieve remarkable performance in some cases, the current scalable parallel high-end computing systems are not well suited to many applications of strategic importance to the nation. To ensure that U.S. scientists continue to have access to computers of the highest possible power, funding should be focused on innovative architectures, hardware technologies, and software strategies that overcome the limitations of today's systems. Without major increases in funding in these areas, the realizable performance of new machines will fall far short of their potential. We specifically recommend that the Federal program should:

■ Fund research into innovative computing technologies and architectures.

■ Increase support for R&D on software for improving the performance of high-end computing.

■ Drive high-end hardware and software computing research by establishing the goal of attaining a sustained petaop performance on real applications by 2010.

■ Fund the acquisition of state-of-the-art high-end computing systems to support science and engineering research and ensure that these systems are networked and available on a competitive basis to the research community.

■ Expand the Federal High End Computing and Computation (HECC) program to include all of the major elements of the government's investment in high-end computing.

4. **Socio-Economic and Workforce Impacts** – In order to fully realize the benefits of information technology, it is important to address the social and economic issues related to technology adoption and diffusion, as well as to ensure that our workforce is properly prepared for the challenges and opportunities of the Information Age. Specifically, the Federal program should:

- Expand Federal research on the social and economic impacts of information technology diffusion and adoption.

- Expand Federal initiatives and government/university/ industry partnerships to increase IT literacy, access and research capabilities.

- Increase research funding to help address the shortage of high-technology workers.

- Develop new educational programs to retrain information technology workers whose skills have become outdated.

- Encourage increased participation by women and minorities.

- Increase the annual cap on H-1B visas as a short-term remedy for the shortage of skilled IT workers.

III. Modes of Research Support

The current Federal funding portfolio is an artifact of the historical development of information technology. Much of IT research is still conducted either as an ancillary part of research in another area or in the form of small projects at single institutions. Yet many critical IT research areas require investments that allow a large or medium-sized team with a strategic vision to pursue a focused project for several years.

To achieve a better balance in the funding portfolio, the Committee recommends that the modes of support be significantly broadened. Specifically, the federal government should:

- Diversify the modes of research support to foster projects of broader scope and longer duration. Increase the emphasis on projects involving multiple investigators over several years.

- Fund virtual centers for "Expeditions into the 21st Century." Much like Lewis and Clark opened the west, virtual centers focused on future technologies and applications can, by making bold assumptions about the future, give us key research insights into the manifold possibilities of the 21st century technologies.

- Establish a program of Enabling Technology Centers. These centers would create and apply new information technology to particular applications domains of importance to the Nation.

12

IV. Management of Federal IT Research

Building a Federal IT research program suited for the needs of the Nation in the 21st century will require new management strategies. A new approach is demanded by the nature of the research itself, the reality of Federal budget constraints and the need to maintain a small, efficient and coordinated research management process. We also need to closely couple IT research with research involving new applications of IT, and the new power the technology provides for linking research managers located in many parts of the country. It is essential that the system put in place:

■ be positioned to review the entire IT research budget.

■ restore the balance between fundamental and applied research.

■ employ a systematic review by participating federal agencies and the private sector.

To achieve these goals we recommend that the existing Federal Information Technology management structure be enhanced as follows:

■ Designate a lead Federal agency for coordinating information technology research. The most logical choice for this role is the National Science Foundation (NSF).

■ Expand the current coordination mechanisms already in place to include the entire federal IT R&D endeavor.

■ Establish a comprehensive annual review of research programs by the coordination committee, with advice from the Advisory Committee, to ensure that those programs are achieving the goals set out for them.

V. Conclusion

Information technology research is essential for the continued growth of the economy and for the solution of some of the most critical problems facing the nation. Unless steps are taken now to reinvigorate federal research in this critical area, we could see a significant reduction in the rate of progress over the coming decades. The cost to the nation of such a reduction would be significantly greater than the investments needed to address the problem now.

1. Information Technology: Transforming our Society

Information technologies are becoming an integral part of people's lives, businesses, and society in general. Advances in microprocessors, memories, storage, software, and communication technologies make it possible to build computers and computing devices that are increasingly affordable, as well as to enable the development of increasingly powerful systems at reasonable costs. The wide acceptance of Internet standards and technologies is helping us build global computer networks capable of connecting everything and reaching everyone.

Since ancient times, networks have offered opportunities for growth and innovation and have supplied structure to our economic and social systems. From the roads and aqueducts of the Roman Empire, to nineteenth century continental railroad systems, to the telecommunications, broadcast, and satellite networks of the twentieth century, networked capabilities have allowed us to overcome barriers of time and space, and to access and open new frontiers for human interaction and ingenuity.

Now, as we approach the new millennium, it is clear that the "information infrastructure"—the interconnected networks of computers, devices, and software—may have as much or greater impact on worldwide social and economic structures than all networks that have preceded them. The advances in computing and communications technologies of the last decade have already transformed our society in many ways. These advances have transformed the ways in which we view ourselves, our relationships with each other and with other communities, and the ways in which we obtain a variety of services, ranging from entertainment and commerce to education and health care. Even so, we have only just begun to grasp the opportunities and to experience the transformations that will occur as these technologies mature.

A significant portion of our national progress in computing and communications over the past decade has been leveraged from the Federal research programs established by the High Performance

Computing Act of 1991 (P.L. 102-194). These programs comprised the High Performance Computing and Communications (HPCC) initiative, which was responsible for moving the U.S. into an era of teraflop computers and gigabit networks. The focus of the HPCC initiative was a set of Grand Challenges, difficult scientific problems whose solutions yielded new scientific understanding while simultaneously advancing high-performance computing, communications and networking.

To ensure a rapid, smooth, and extendible transition into the coming era of computing and communications, the President's Information Technology Advisory Committee has identified ten critical "Grand Challenge Transformations." These information technology (IT) transformations will affect how we communicate, how we store and access information, how we receive medical treatment, how we learn, how we conduct business, how we work, how we design and build things, how we conduct research, how we sustain the environment, and how we manage our government in the next millennium.

Exploring these dynamic transformations enables us to identify common information technology challenges critical to our Nation's future and provides a framework for our recommendations for Federal research investments.

Transforming the way we communicate

Vision: One billion people worldwide can access the Internet simultaneously and engage in real-time electronic meetings, download the daily news, conduct financial transactions, or talk to friends and relatives around the world. This can be done regardless of the language in which the participants are speaking, since language translation can be done instantaneously, and regardless of physical limitations, because devices can accept and provide input and output in many ways.

The Internet lies at the heart of our communications revolution. But, the current Internet must scale so that it can accommodate anticipated growth in usage and demands for reliability comparable to that of the modern telephone system. New and improved modes of human interaction with computers must be developed to significantly enrich and simplify the way we communicate. We must understand the behavior of extremely large-scale and complex systems and address the potential fragility of large numbers of autonomously interacting systems of software. Global networking raises a host of international issues and even poses questions about the nature of national boundaries as information flows across them invisibly and multinational corporations use worldwide networks to pursue their global interests. Perhaps the biggest challenge of all is to understand how human beings can best take advantage of the new electronic communication possibilities, both one-on-one and in groups.

Transforming the way we deal with information

Vision: An individual can access, query, or print any book, magazine, newspaper, video, data item, or reference document in any language by simply clicking the mouse, touching the computer screen, talking to the computer, or blinking an eye. Individuals can easily select among modes of presentation: data, text, images, or audio. Information can be referenced and derivations can be incorporated in many new ways, adding value and revealing insights through networked and software-enabled tools.

This transformation requires significant improvements in data access methods, including high performance file systems and tools to help individuals locate information and present, integrate, and transform the information in meaningful ways. Systems will require interfaces accessible both to experts and novice or infrequent users regardless of physical ability, education, or culture. Multi-modal human-computer interaction technologies are needed including speech, touch, and gesture recognition and synthesis. There are research requirements for topics ranging from network reliability and bandwidth, to scalable software support and high-performance computing, and robust, reliable, secure ways to deliver—and to protect—critical information. Challenging issues regarding dissemination of information in electronic form—including copyright, intellectual property rights, and realistic business models—remain important policy and research topics.

Transforming the way we learn

Vision: Any individual can participate in on-line education programs regardless of geographic location, age, physical limitation, or personal schedule. Everyone can access repositories of educational materials, easily recalling past lessons, updating skills, or selecting from among different teaching methods in order to discover the most effective style for that individual. Educational programs can be customized to each individual's needs, so that our information revolution reaches everyone and no one gets left behind.

In education, information technology is already changing how we teach, learn, and conduct research, but important research challenges remain. In addition to research to meet the scalability and reliability requirements for information infrastructure, improvements are needed in the software technologies to enable development of educational materials quickly and easily and to support their modification and maintenance. We know too little about how best to use computing and communications technology for effective teaching and learning. We need to better understand what aspects of learning can be effectively facilitated by technology and which aspects require traditional classroom interactions with the accompanying social and interactive contexts. We also need to determine how best to teach our citizens the powers and limitations of the new technologies and how

to use these technologies effectively in their personal and professional lives.

Transforming the nature of commerce

Vision: Any company can be easily reached by its customers, regardless of location. It can receive immediate customer feedback, and rapidly adjust marketing strategies or product inventories based on that feedback. Consumers can shop for the best products, services, and prices from the convenience of their hotel room, home, or office. Electronic purchases can be made securely, providing suppliers and retailers with immediate access to cash generated by sales and consumers with automated statements detailing spending and purchases that allow for improved personal financial management.

Electronic communication is dramatically changing how commercial transactions between companies are conducted, how digitally based goods and services are distributed, and how retail sales are made. Companies are using information technology to get closer to their customers and suppliers. Technology is also helping to reduce paper work and purchasing costs by streamlining the acquisition process and allowing companies to more efficiently find the best suppliers. Privacy and security are critical research topics to ensure consumer confidence in electronic commerce. Reliability of the communication networks, computers, and business applications are vital to the success of U.S. companies.

Transforming the nature of work

Vision: The workplace is no longer confined to a specific geographic location, as workers can easily access their tasks and colleagues from alternate locations or while en route. Workers have access to jobs without regard to physical proximity to major metropolitan areas. They can choose where they live based on nearness to family or lifestyle preference rather than job market opportunities. A highly flexible workplace is able to accommodate each individual's needs, from working parents to workers with disabilities.

By some projections, as many as 15 million U.S. workers will become telecommuters over the next decade, resulting in enhancements in worker productivity and organizational flexibility as well as environmental benefits. To support large numbers of workers in non-traditional office settings, including the rapidly growing number of home businesses, we will need high-speed networking capability, equally available to all workers, regardless of physical location or physical disability. Software technologies that allow work teams to collaborate effectively will be needed, and privacy and reliability of the information infrastructure are critical. The social and economic implications of telecommuting need to be studied.

Already an important part of large-scale agribusiness, computing is having a major impact on family farms, which can now access the

latest in weather, crop, transportation, and market information online — assuming affordable network connections are available in their sometimes remote locations. Computing and communications are also dramatically altering the skill base that workers need to perform their jobs. We need to determine how both employers, employees, and the self-employed can respond effectively to these changes.

Transforming the practice of health care

Vision: Telemedicine applications are commonplace. Specialists use videoconferencing and telesensing methods to interview and even to examine patients who may be hundreds of miles away. Computer-aided surgery with Internet-based video is used to demonstrate surgical procedures to others. Powerful high-end systems provide expert advice based on sophisticated analysis of huge amounts of medical information. Patients are empowered in making decisions about their own care through new models of interaction with their physicians and ever-increasing access to biomedical information via digital medical libraries and the Internet.

Future requirements for electronic medical records and health-system intranets will lead to increased reliance on the national infrastructure for communications, data sharing, and direct provision of care at a distance. Privacy and knowledge repositories are important research topics. Robotics and remote visualization methods, supported by high-reliability, low-latency communications, are needed to support applications such as telepresence surgery.

Transforming how we design and build things

Vision: Complex products and structures can be designed via computer simulations that accurately represent the physical properties of the systems being built. Designers, manufacturers/builders, suppliers, and end-users participate in the design process, providing immediate feedback. Multiple designs and manufacturing processes can be rapidly explored, resulting in safer products, high quality, and lower costs.

Global competition continues to keep pressure on United States manufacturers to attract new customers and retain current customers by increasing productivity, reducing cost, improving quality, maintaining maximum flexibility, and reducing cycle time. Information technology has and will continue to revolutionize the entire product development design cycle. High-end computing technologies are needed for concept design, simulation, analysis with interactive control and computation steering, the mining of archived data, and the rendering of data for display and analysis. There is a critical need for engineering development processes that will be linked in both directions with business processes like planning, purchasing, scheduling, and investment and cost management, as well as networked computers that allow simultaneous modification of a standard product to meet customers' needs.

18

Information Technology:

Transforming how we conduct research

Vision: Research is conducted in virtual laboratories in which scientists and engineers can routinely perform their work without regard to physical location—interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries. All scientific and technical journals are available on-line, allowing readers to download equations and databases and manipulate variables so one can explore the published research interactively.

High speed computers and networks are enabling scientific discoveries across a broad spectrum—from mapping the human brain to modeling environmental climate change. Research problems are becoming more complex and interdisciplinary in nature. As a result, researchers are finding innovative ways to collaborate with colleagues. Key research technologies include high-end computing to allow higher fidelity models of complex physical phenomena, advances in collaborative environments, visualization of complex datasets, and management of very large datasets and databases.

Transforming how we deal with the environment

Vision: Reliable climate models permit us to determine the rate and regional distribution of climate change to support accurate projections by sector and region. Sophisticated models accurately predict the response of ecosystems to changes in temperature, water availability, and atmospheric composition. Fully integrated models allow scientists and policy makers to consider information on climate trends, population trends, resource utilization, and the value of natural and economic resources when making decisions regarding technically feasible and cost-effective options to reduce or adapt to climate change.

In order to support national and international energy and environmental policy, the U.S. requires an unprecedented acceleration and extension of climate modeling research to improve the accuracy of local and regional forecasting. Progress in this area depends on improvements in computational methods. This requires orders of magnitude increases in computing capability to deal with the immense range in time and spatial scales of transport. The capabilities described above require other advanced information technologies such as improved numerical methods and algorithms, tools for data storage, management, analysis and visualization, software development and testing techniques, and advanced networks for distributed computing.

Transforming government

Vision: Government services and information are easily accessible to citizens, regardless of their physical location, level of computer literacy, or physical capacity. Intelligent systems guide citizens by providing a one-stop shopping experience for locating requested information. Documents and forms can be accessed, completed, and

submitted electronically. Automated business processes allow nearly instantaneous response to citizens' requests. In times of natural emergencies, emergency crews have instant access to three-dimensional building models, risk analysis and assessment, high resolution local weather predictions, stress analyses of damaged structures, rapid evacuation planning tools, and emergency agency coordination.

This transformation requires significant improvements in systems and methods for accessing data, including high performance file systems and tools to locate and present information. Robust, reliable, and secure networks and software to deliver and protect critical information are important research topics.

Crisis management research topics include wireless data network technologies and adaptive networks, improved computational environments to support modeling and simulation, and collaborative environments that allow crisis management officials access to both human expertise and digital information, such as building drawings.

Conclusions

The positive impact these transformations can have on our Nation's future is extraordinary, but our success is not guaranteed. The success of each transformation will depend on the results of aggressive, well managed Federal research programs aimed at solving sophisticated technological problems and developing the underlying infrastructure, technologies, and products necessary to ensure positive and sustainable transformations for our country.

Long-term Federal investment in these research areas is necessary to incubate ideas to the point of clear commercial viability. Publicly funded research supports exploratory work, allows the pursuit of ideas that may lead to success in unexpected ways, and creates opportunities that industry can exploit in the medium and long-term, creating jobs and benefits for our children and ourselves. Federal investments drive not only discovery, but also training of our young people and workers who need to upgrade their skills to keep pace with a changing marketplace. A major output of publicly supported research is people—people who form a critical intellectual base for continued IT innovation. These trained professionals will create and develop new ideas, form a talent pool for existing business, and launch new companies.

The following section outlines the Committee's recommendations for increased Federal investments in IT research and development. Because today's IT products are based on yesterday's fundamental research, investment in innovation must go forward so that the IT industry can continue to thrive and U.S. citizens can enjoy the benefits of these innovations.

2. Setting Federal Research Priorities: Findings and Recommendations

2.1 Findings

Government-funded fundamental and applied research in information technology has been an enormous source of innovation. The results have been made readily available to industry. Testbed activities involving academia, government research facilities, and industry have served as powerful avenues for technology transfer into the private sector, where industry and government have benefited from the resulting products and services.

Today we enjoy the economic, strategic, and societal benefits of well-placed investments in long-term, wide-ranging information technology research begun during the Eisenhower and Kennedy Administrations. These modest investments have yielded massive economic benefits to the Nation. The empirical evidence is unequivocal: growth in today's information technology (IT) sector vastly outstrips the current growth of all other sectors of the economy. The Federal Reserve reports that during the past five years production in computers, semiconductors, and communications equipment quadrupled at a time when total industrial production grew by 28 percent. These three industries account for one-third of the total growth in production since 1992.

No other sector contributes nearly as much to the growth of our economy. The businesses spawned by these technologies employ millions of Americans in manufacturing and information processing jobs that pay wages well above the national average.

History suggests that, to be successful, Federal research investment must be sustained and flexible. Federal policies must support, encourage, and help coordinate long-range technological development. Federal research and development (R&D) programs must be well designed and must not subsidize activities best left to the private sector. Only in this way can the Federal investment spur those critical areas of technology that either industry neglects, or, which the Government overlooks in the normal course of business because they cut across Federal agency missions.

Finding: Total Federal information technology R&D investment is inadequate.

The non-inflationary growth in our high-technology industries is important to U.S. world leadership and the creation of whole new industries with a substantial number of high-paying jobs. Furthermore, information technology's importance goes far beyond its economic impact because it is fundamental to the solutions of many problems of national importance. But the amount of Federal R&D investment has been, at best, steady, and compromised by a shift toward applied R&D. The Committee finds that the amount of Federal research investment in information technology has not kept pace with IT's growing economic, strategic, and societal importance to the Nation.

There is no shortage of research ideas, as evidenced by the number of proposals in computer science and information technology competitions. For example, the recent competition in Knowledge and Distributed Intelligence (KDI) sponsored by the National Science Foundation (NSF) drew over 1100 letters of intent and over 850 full proposals even though it had been announced that at most seventy-five projects could be funded. The response to the Department of Energy (DoE) Accelerated Strategic Computing Initiative (ASCI) level 2 centers competition was similar. The reason for these extraordinary numbers of responses is that funding for information technology is extremely tight. Researchers are forced to participate in nearly every competition for which they might qualify. The end result is that researchers are spending increasing percentages of their time in proposal writing to the detriment of research itself, and many good ideas are still not being funded.

This trend is not just bad for information technology researchers, it is bad for the Nation. Our ability to produce reliable software, build an information network on which the Nation can run, and produce the high-end computing systems needed for advanced science, engineering, and defense tasks is threatened by inadequate investments in research and development. By neglecting research, we do more than deplete the stock of fundamental knowledge. We endanger the long-term effectiveness of the entire R&D system and threaten U.S. leadership in the emerging 21st-century information-based economy.

Finding: Federal IT R&D is excessively focused on near-term problems.

The NSF defines basic research as the study of the "fundamental aspects of phenomena and of observable facts without specific application toward processes or products." In contrast, "applied

16

research" is aimed at determining the means to meet specific needs, and "development" is defined as the systematic use of knowledge to produce useful materials, devices, or methods. These definitions are widely used in Federal policy and budget accounting, but they accurately describe only part of the nature of R&D. R&D is a complex non-linear interaction between concepts and theories, data and experiments, and new products and processes. Basic research is a critically important part of this interwoven system.

During the past decade both industry and Government have altered the balance between basic research and the later stages of technology development and commercialization. At the same time, major corporations have cut back on fundamental research expenditures, shifting staff from centralized laboratories to operating divisions where applied work is closely tied to commercial products and processes. In both the public and private sectors, the interacting reasons are (1) downward budget pressures, (2) increased focus on mission, (3) the difficulty of demonstrating the transition of long-term research to near-term product, and (4) pressures for organizations and individuals to avoid risk.

Although total Federal spending for R&D has remained steady, there has been a marked shift toward support for applied R&D. For example, the Defense Advanced Research Projects Agency (DARPA), which funded much of the innovative research in the 1980's, now judges all information technology funding in terms of its impact on the warfighter. In the process of making this change it has decreased the time horizon for potential technology transfer. In the early 1990's, DARPA split the Information Systems Office off from its Information Technology Office to address specific military systems. Nevertheless, total funding for basic research in the DARPA Information Technology Office is less than $20 million out of a total office budget of more than $300 million, an inadequate investment.

Much of this R&D investment restructuring was essential in order for industry and the Government to maintain competitive footing in the global marketplace and to maintain readiness against our present and future adversaries. However, this restructuring came at a high price: a serious decline in basic research activities. Research in computer science is a good example. In 1995, by the Federal Government's own measure [NSF Science and Engineering Indicators, 1996], more than two out of every three Federal dollars spent on academic research in computer science was for applied work.

The Committee finds that the Federal agenda for IT R&D has moved too far in the direction of near-term applications development, at the expense of long-term, high risk, fundamental investigations in the underlying issues confronting the field. Currently, too high a

percentage of research funding comes from mission-oriented agencies whose main goal is not so much to advance the knowledge-base in information technology as it is to solve the immediate problems confronting those agencies.

Economic growth and defense leadership, if based on evolutionary improvements to yesterday's research results, are not sustainable. Nor is the rest of the world standing still in seeking economic advantage from new information technologies. By the Committee's own calculation, basic research spending may be as low as five percent of the total information technology R&D budget. As a result, promising long-term research is being passed over in order to meet the goals of near-term technology development.

It is time to swing the pendulum back in the other direction and to strike a proper balance. We need more fundamental research—the kind of groundbreaking, high risk/high return research—that will provide the ideas and methods for new disciplinary paradigms a decade or more in the future. We must make wise investments that will bear fruit over the next forty years.

2.2 Recommendations for Research

The current boom in information technology is built on fundamental research in computer science carried out more than a decade ago. There is an urgent need to replenish the knowledge base. We must aim to leave a legacy to future generations based on an intelligent, well-planned, well-disciplined investment in information technology that is commensurate with its role in the Information Age.

Recommendation: Create a strategic initiative in long-term IT R&D.

The Committee recommends that the President create a strategic initiative to invest substantial additional funds in long-term research in fundamental issues in computing, information, and communications.

The Administration's fiscal year 1999 proposal provides a good start. The Committee applauds the recently announced 21st Century Research Fund. Other steps in the right direction include:

- $850 million for large-scale networking and high-end computing and computation, including $110 million for the Next Generation Internet (NGI)

- NSF's $78 million research program in Knowledge and Distributed Intelligence

- the Department of Energy's (DoE) $517 million Accelerated Strategic Computing Initiative (ASCI)

■ major increases in fundamental research and exploratory development/applied research investments by the Department of Defense (DoD)

However, these programs do not go nearly far enough, either in scale or in scope. There is inadequate provision for sustained well-funded investigations of difficult problems of long-term fundamental importance. In order to maintain U.S. leadership, the fiscal year 2000 proposal—the "millennium budget"—should be guided by the basic principle that Federal support for information technology must be increased to bring it in line with its importance to the economy.

Recommendation: Increase the investment for research in software, scalable information infrastructure, high-end computing, and socio-economic and workforce impacts.

Four areas of the overall research agenda particularly need attention and must be a major part of the strategic initiative:

■ Software – Methods for efficiently creating and maintaining high-quality software of all kinds and for ensuring the reliability of the complex software systems that now provide the infrastructure for much of our economy.

■ Scalable Information Infrastructure – Techniques for ensuring that the national information infrastructure— including communications systems, the Internet, large data repositories, and other emerging systems—is reliable and secure and can grow gracefully to accommodate the massive numbers of new users and applications requiring high bandwidth that are expected over the coming two decades.

■ High-end Computing – Continued invention and innovation in the development of fast, powerful computing systems. These high-end systems are needed to implement critical applications ranging from aircraft design to weather and climate modeling.

■ Socio-economic and workforce impacts – Methods for addressing social, political and legal issues and for ensuring that our educational systems properly prepare our workforce for both the challenges and opportunities of the information age.

The Committee recommends increasing investments in research in these specific areas to meet critical national economic and defense needs and maintain U.S. leadership, as detailed below.

25

3. Research Focal Points and Societal Implications

3.1 Software Research

Software is the new physical infrastructure of the information age. It is fundamental to economic success, scientific and technical research, and national security. Software is increasingly important for commerce, for communication, for access to information, and for the physical infrastructure of the country. The emergence of cheaper, faster microprocessors has allowed more and more functions to be performed by software.

While we may think of the phone system, the Internet, or even a camera or a car as devices, these devices cannot function without software. We rely on software to work without fail, to be modifiable as requirements change, and consistently to provide more functions with better performance.

However, because the demand for software has grown at such an explosive rate, it now far outweighs the resources we have to produce it. The result is that desperately needed software is not being developed. Furthermore, the Nation currently depends on software that is fragile, unreliable, and extremely difficult and labor-intensive to develop, test, and evolve. Our ability to construct the needed software systems and our ability to analyze and predict the performance of the enormously complex software systems that lie at the core of our economy are painfully inadequate. We are neither training enough professionals to supply the needed software, nor adequately improving the efficiency and quality of our construction methods. The recent Government emphasis on short-term, applied R&D has hurt software research, diminishing the amount of advanced software technology available for commercialization.

3.1.1 Findings

Finding: Demand for software far exceeds the Nation's ability to produce it.

The explosive growth of information technology has fueled an unprecedented demand for new software. Software is needed to support new products, to provide fundamental services on the Internet, and to solve important national problems. At the same time,

the resources needed to develop this software have not kept pace with the demand, producing what might be called a "software gap."

An interaction of factors has caused this software gap: accelerated demand for software, increased complexity of systems, labor-intensity of development, variable quality in the labor pool, labor shortages, and lack of adequate science and technology to support robust development. Since cost-effective improvements in hardware lead to a strong demand for more software, the demand will continue to accelerate. Today's systems and applications software are substantially more complex than in the past. Software systems are now among the most complex of human-engineered structures.

This situation threatens to inhibit the progress of the current boom in information technology and may threaten the health and welfare of the Nation by reducing the rate at which solutions to software-intensive problems, like aviation safety and crisis management, can be solved. The Federal Government must take steps to address the situation by investing in research on new strategies to improve software development productivity and by helping to increase the pool of information technology professionals capable of developing good software.

Finding: The Nation depends on fragile software.

The Nation needs robust systems, but the software our systems depend on is fragile. Software fragility is its tendency not to work properly—or at all—for long enough periods of time or in the presence of uncontrollable environmental variation. Fragility is manifested as unreliability, lack of security, performance lapses, errors, and difficulty in upgrading.

Examples can be found everywhere, from our huge information systems for air-traffic control to the personal computers on our desks, from the Pentagon to the Internal Revenue Service (IRS). One aspect of our software's lack of security is evidenced by the fact that teenage hackers have easily penetrated our telephone and military systems; in reality the software-security problems we face go far beyond calculated external attacks.

The Federal Aviation and Aeronautics (FAA) and IRS systems have proved to be difficult to upgrade. Large telecommunications networks have crashed, and banks have been robbed electronically. Even after large, expensive testing efforts, commercial software is shipped known to be riddled with errors ("bugs"). Software producers rely on their users to discover the remaining errors in actual use, making it even more likely that our systems will crash.

27

Not only are our products inadequate—so are our processes. The Standish Group reports that 73 percent of software projects are late, substantially over-budget, canceled, or fail outright. The well publicized, potentially catastrophic "Year 2000 problem" is an example of known unreliability and illustrates the difficulty and cost of upgrading to meet new circumstances. Companies spend enormous amounts to back-up their on-line data in order to compensate for the risk that their own systems will corrupt it.

The Nation cannot afford to let the current situation continue. We must commit to develop the science, technologies, and methods needed to build robust systems—ones that are reliable, fault-tolerant, secure, evolvable, maintainable, and cost-effective.

Finding: Technologies to build reliable and secure software are inadequate.

During the past 40 years, computing hardware has seen an increase in performance of at least eight orders of magnitude. However, our ability to develop software has not kept pace with the opportunities those hardware advances provide. Our ability to construct the systems we require and our ability to anticipate the performance of the enormously complex software systems that lie at their core are inadequate.

Large software systems are beyond our capability to describe precisely. Consequently, there is little automation of their construction, little re-use of previously developed components, virtually no ability to perform accurate engineering analyses, and no way to know the extent to which a large software system has been tested.

Having a meaningful and standardized behavioral specification would make it more feasible to determine the properties of a software system and enable more thorough and less costly testing. Unfortunately such specifications are rarely used. Even less frequently is there a correspondence between a specification and the software itself. Often software behavior and flaws are observable only when the program is run, and even then may be invisible except under certain unusual conditions. Programs written in such circumstances frustrate attempts to create robust systems and are inherently fragile.

Software development relies on individual genius and creativity, and, as with all design-based disciplines, will continue to do so. But it has become clear that the processes of developing, testing, and maintaining software must change. We need scientifically sound approaches to software development that will enable meaningful and

practical testing for consistency of specifications and implementations. This requires long-term research in languages, theories, simulation, analysis, and testing that could lead to standardized multilevel mechanisms similar to those which have created the success in computer-aided design for digital hardware.

The construction and availability of libraries of certifiably robust, specified, modeled, and tested software components would greatly aid the development of new software. Libraries of software components for developing business applications are beginning to be constructed commercially, but only in limited circumstances.

In addition to research on the generic construction of software artifacts, there must be continued research focused on the domain-specific aspects of particular kinds of software systems. For example, real-time control, scene recognition systems, ubiquitous computing, and collaborative decision-making have very broad and important military and civilian applications. The algorithms and information structures required for these and other important domains require additional research. Whether the purpose of software is systems-oriented (e.g., an operating system or a compiler) or applications-oriented (e.g., a billing system or an animation), the software technology must continue to advance.

Finding: The Nation is under-investing in fundamental software research.

Over the past decade the U.S. has under-invested in research to create fundamentally new software technologies. Most of today's software technology is based on research performed 15 or more years ago. If we fail to invest in far-reaching, high-risk research now, on what ideas will the commercial advances of the year 2015 be based?

In recent large Federal information technology initiatives, the Committee found systematic under-investment in the software side of the research agenda, leaving a growing gap between the theoretical potential and actual performance of hardware. The Federal High Performance Computing Program (HPCC) plan, for example, stated, "advances in software will be critical to the success of high performance computers with massively parallel architectures." [1] HPCC researchers, however, were encouraged to focus on the immediate use of their results on Grand Challenge problems or in semi-production parallel computer systems. This successful, short-term strategy emphasized software to solve particular scientific or

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[1] Executive Office of the President, Office of Science and Technology Policy, "The Federal High Performance Computing Program," document, September, 1989.

systems problems, but it failed to develop the fundamental software technology needed to solve wider classes of problems such as interoperability across different computing architectures.

Additionally, under-investment in long-term software research has interrupted the pipeline that produces software research professionals. The Committee strongly believes that increases in research funding are needed to develop a large cadre of promising young researchers.

3.1.2 Recommendations

Software is increasingly important to the fabric of our society. By failing to improve the quality of the software we develop and use and the processes used to develop it, we put the Nation at risk. Long-term research is needed to strengthen our software enterprise. That research is not being adequately supported. This research should be closely coordinated with research undertaken in response to the President's Commission on Critical Infrastructure designed to protect the nation's infrastructure from intentional attacks.

The Committee recommends that a variety of additional investments be made to enable fundamental improvements in the Nation's software quality and its development processes. In particular, major improvements must be made to methods for software development, verification and validation, maintenance, user interfaces to computing systems and electronically represented information, software for high-end computing, and software to support emerging ubiquitous and collaborative computing.

Recommendation: Fund more fundamental research in software development methods and component technologies.

The Committee recommends that research in software methods, especially in the area of automated support for software development and maintenance, be aggressively pursued. Such research should explore and create:

- component-based software design and production techniques, and the scientific and technological foundations needed for a software component industry

- techniques for using measurably reliable components and their aggregation into predictably reliable and fault-tolerant systems

- theories, languages and tools that support automated analysis, simulation, and testing of components and their aggregation into systems

- techniques for aggregating provably secure components into provably secure systems

■ standardized protocols and data structures to promote interoperability of applications running in parallel across wide-area networks

Recommendation: Sponsor a national library of software components in subject area domains.

The Committee recommends that a program be established—based on the recommended research on software development methods and component technologies—to create a National Electronic Library of reusable software components in areas useful for Science and Engineering research and education. This library would initially be a way to test components and component technologies. The Committee expects that standards will develop based on technologies for robust software and will enable widespread registration and sharing of software. In this way, the library can evolve into a widely used resource. The Committee is fully aware of previous attempts to establish national software libraries as well as the reasons for their lack of success. However, the Committee feels that this is still a desirable goal and recommends that funding be directed to address the technical problems associated with the previous failures.

The technical problems to be addressed include mechanisms for high-level specification of components, for reliability and performance guarantees, for evolution of components over time, and for solutions to other unanticipated barriers to effective use of the components. In addition, methods are needed for effective discovery of existing components, for appropriate organization of the library, for appropriate intellectual property safeguards, and for integrity of the collection with respect to tampering of various kinds. It is anticipated that as the technology matures, researchers will contribute software components to the library, and that those components that are accepted will have passed acceptability tests. The Nation's information infrastructure will be used to provide widespread access to the library.

Recommendation: Make software research a substantive component of every major IT research initiative.

In the past, major initiatives, such as HPCC, have suffered from under-investment in software research. When considering new initiatives like the ones proposed later in this section, we must ensure that the software research necessary for success is included.

For example, we cannot build a scalable information infrastructure without an adequate investment in the software that will provide services on that network. For this reason, the Committee recommends

26

in Section 3.2 substantive new software investments to support scalability, distribution and reliability.

Similarly, there is a continuing need to raise the level at which the users of high-end computing create applications software and migrate their software solutions to new architectures. Thus an adequate investment in software to support those activities is called for in Section 3.3.

In short, Federal research support programs have a history of underestimating the software research and development investment needed for success. This tendency must be reversed if new information technology initiatives are to have the impact the Nation needs.

Recommendation: Support fundamental research in human-computer interfaces and interaction.

There are many facets to human-computer interfaces and interactions. We must provide easy access to all people, regardless of economic circumstances, physical impairment, or intellectual limitations. To that end, user interfaces must become considerably richer, depending less on textual interfaces and manual dexterity, rather taking more advantage of the decreased cost and increased miniaturization of audiovisual devices, increasing the use of natural language, and providing more assistance to the user, through techniques ranging from help systems to inference. Progress in ease-of-use is a good example of the coupling of software advances with those of the underlying hardware devices.

The spectacular advances in computing power and new display technologies can provide a deeper understanding of information and data. Full-immersion environments such as "CAVEs" are beginning to explore some of the implications, but substantial funding for hardware to enable software research in this area will be needed for the next breakthrough.

3.1.3 Major Recommendation

Make fundamental software research an absolute priority.

The Committee recommends that the Government make fundamental research in software both for computer systems engineering and for applications one of the Nation's highest R&D priorities. We recommend that a focus on software research be a mandatory element of all the Expeditions proposed in Section 4.2.2. In addition, significant added research funding within current modes of funding should be focused on fundamental software research.

Research Focal Points and Societal Implications

3.2 Scalable Information Infrastructure

Over the next decade, the information infrastructure will continue to lead to dramatic transformations in our Nation's economy, defense, and society. Information technology will play an unprecedented role in eliminating critical barriers to progress, such as geographic distance, time to accomplish tasks, separation of people from resources, and outdated organizational structures. Never before has there been an opportunity on such a grand scale to harness such a diverse range of technologies and to integrate them into such a pervasive array of interconnected information systems.

The term information infrastructure is meant to convey the sense that the creation, storage, retrieval and exchange of information needs infrastructure in the same way that automobiles need an infrastructure of roads, service stations, standards, and laws. Information infrastructure is the interconnected series of telecommunications networks and computer based services necessary for people to communicate, access information and services, work productively, and be entertained. The Committee uses the term scalable information infrastructure to emphasize the need for these networks and computer based services to scale—that is, to handle increasing numbers of users, diversity of services, and growing service demands.

Building a scalable and robust information infrastructure is an extremely challenging problem. Many of today's technologies will not scale and require significant redesigns to handle the huge loads. Presently, there is insufficient Federal funding aimed directly at the challenge of scaling the infrastructure and there are too few computer scientists dedicated to understanding the scaling problem. The broad challenge of scaling the information infrastructure demands precisely the kind of cross-cutting research—in network modeling and analysis, connectivity, performance of network services, network operations and management, quality of service, information management, reliability, and security—that is appropriately the role of Federal R&D. As we come to depend more and more on the information infrastructure, there is an urgent need to invest in strategic R&D that will ensure the quality and responsiveness that the public expects and that critical applications require.

3.2.1 Findings

Finding: The Internet has grown well beyond the intent of its original designers.

The Internet, which connected 2,000 computers in 1985, now connects 30 million computers, and is continuing to double in size every year. By the end of 1997, it was estimated that more than 100 million people worldwide were using the Internet. The number of Internet users worldwide could surpass one billion as early as 2005. In addition to growing in terms of people accessing the Internet, the Internet is growing in terms of the types of services provided over the

33

network. Satellite and wireless systems will soon provide users with "anytime, anywhere" communications. Directory and search services help users locate important resources on the Internet. Electronic mail servers manage and store critical information. Authentication and electronic payment services handle more and more of the Nation's commerce. Building blocks for new applications are being developed. Examples include digital signatures, secure transactions, modeling and simulation software, shared virtual environments for collaboration, intelligent agents, tools for discovering and retrieving information, speech recognition, and low-cost networked sensors.

Finding: Our Nation's dependence on the Information Infrastructure is increasing daily.

Within the next two decades, computer networks will have penetrated more deeply into our society than any previous network, including the telephone, radio, television, transportation, and electric power distribution networks. Soon we will depend on the information infrastructure for delivery of routine services such as banking and financial transactions, purchases of goods and services, entertainment, communications with friends, family, and businesses, as well as for vital services, such as Government and medical services. As users come to depend on the Internet each and every day, and as billions of dollars are transacted using electronic commerce, the information infrastructure becomes more critical to our Nation's well being.

While America leads the world in developing and applying information and communications technologies, it is crucial that the U.S. continue to invest in these technologies. At stake is the technology that will determine our Nation's ability to sustain its economic well being, to compete successfully in the global marketplace, and to enable affordable national security.

Finding: We cannot safely extend what we currently know to more complex systems.

The continued growth of the Internet—in terms of the number of users, the proliferation of new and more demanding services, changes in underlying technology, and the growing heterogeneity of the networks and applications—greatly increases the complexity of the infrastructure. For instance, the largest packet network ever built is many orders of magnitude less complex than what must be built to accommodate the anticipated number of users and services. We cannot safely extend current technology to new networks that are orders of magnitude more complex and that can carry many more kinds of traffic, including voice, and expect to achieve the kind of

quality and reliability represented by today's U.S. telephone systems. While we understand how to build some, but not all, of these individual elements of the future infrastructure, we do not know how to make these elements work together in a reliable, efficient, and robust way. Similar problems will arise when we try to build scalable services, say, a search engine that can index terabytes of data or a payment service that can process millions of transactions per second.

Finding: Learning how to build large-scale, highly reliable and secure systems requires research.

The future information infrastructure must provide high performance, robust, reliable, and secure connectivity and functionality among an ever-increasing number of computers. Networks of computers filled with disparate software represent a system whose combinatorial character is beyond easy comprehension. Efforts are needed to study, analyze, and develop understanding about the behaviors of such large and complex computer systems.

We need a better scientific base to build the links and nodes of the expanding information infrastructure that represent radically different scales of usage and traffic. There are many technical obstacles— issues of integration, privacy of data, security, reliability, ease of use, and ease of management that stand between the current state of the art and the sort of global, ubiquitous, heterogeneous infrastructure that is implied by growing to one billion users on the Internet.

To support the growing demand and dependence on the information infrastructure, advances are needed in at least five major dimensions:

■ Scaling to provide robust, high-speed access, with assured quality-of service when required. These advances will improve the quality of interaction.

■ Scaling to provide multi-faceted access. This scaling will create new ways for people to connect.

■ Scaling to provide ubiquitous access. These advances will increase the number of people with continuous access to information.

■ Scaling of the infrastructure services to reliably handle many users and requests. These services include authentication, resource directories, search engines, banking, and many others. Advances in this area will improve the quality of information.

■ Scaling of the security infrastructure to safeguard intellectual property rights, to protect against all types of failures or

30

attacks, and to provide privacy of access when needed. These advances will make information and the infrastructure more trustworthy.

3.2.2 Recommendations

Recommendation: Increase funding in research and development of core software and communications technologies aimed directly at the challenge of scaling the information infrastructure.

The Committee recommends that a substantial funding increase be invested in the following three key research areas that are critical to scaling the information infrastructure:

■ **Scalability.** Improving the information infrastructure for the Nation requires using the highest performance to meet the practical needs of millions of simultaneous users. The future information infrastructure will consist of elements that are of much greater diversity and represent as much as a million or more factor of improvement in performance than those of today. Research is needed to better understand how to build models of these large, complex systems. Traffic characterization models and models of the effect of aggregate demand are needed, as well as the ability to simulate a network under various conditions. Also needed are test and measurement tools, as well as supporting standards that provide flexibility and scalability. Software algorithms for scalable and secure services require improved schemes for filtering vast amounts of information, for coping with inaccurate data and with intrusions, and for processing huge numbers of user transactions.

■ **Physical distribution.** A better information infrastructure will emphasize geographical distribution with its limitations on bandwidth, increase in latency of communication, and additional challenges in secure and reliable communication. As the number of computers connected to the network increases, addressing and routing becomes more difficult, especially as hosts become mobile, as applications become more demanding, and as networks seek to provide multiple levels of service to meet different application needs. Allocating network capacity and dealing with congestion also become more problematic as usage expands. Lastly, ensuring interoperability—the ability of heterogeneous hardware and multi-vendor software to interoperate—will become more challenging. Research is needed to achieve progress in each of these areas. Government can also play an important role by supporting testbeds, such as the Next Generation Internet (NGI), and demonstration projects that allow early deployment of maturing technologies.

36

■ **Usability.** The fundamental challenge to greater acceptance and use of information technologies is to make them more usable. The acceptance and popularity of Web browsers demonstrate the importance of user models, human factors, and other areas where research is critically needed. To achieve an information infrastructure in the fullest sense—an information infrastructure that reaches ordinary citizens—these efforts must be extended to address intuitive models of use and user interface technologies to enable a class of information appliances that will become a part of everyday life. Intelligent information retrieval systems, systems for understanding speech and pictures, and systems for enabling intelligent dialogues between people and computer systems are capabilities that will build on the High Performance Computing and Communications Initiative (HPCCI) research and enhance the usefulness and level of use of the information infrastructure. In addition, research and development of software technologies such as security, privacy, network measurement and management, database management, transaction processing, application integration, and other capabilities may be less directly visible to individuals but are essential to making computing and communications facilities more usable.

Recommendation: Expand the Next Generation Internet testbeds to include additional industry partnerships in order to foster the rapid commercialization and deployment of enabling technologies.

As the information infrastructure continues to grow in size and complexity, it is important to build testbeds large enough to provide a full system, proof-of-concept testbed for hardware, software, protocols, services, and network management that will be required in the future. The Next Generation Internet (NGI) initiative provides a network testbed. This effort should be broadened into a more comprehensive infrastructure testbed that includes information, commerce, and other services. This testbed should also include industry partnerships, since the cost of building testbeds to experiment with critical design and deployment issues at the scale necessary is beyond the ability of any single company or entity. These partnerships will also foster the rapid commercialization and deployment of enabling technologies.

3.3 High-End Computing

Since its creation under the High Performance Computing Act of 1991, the Federal High Performance Computing and Communications (HPCC) Program has contributed greatly to U.S. technological leadership. The Program has created and disseminated technologies to speed the pace of innovation, enhance national

security, promote education, and help us understand the global environment. Furthermore, yesterday's advances in high-performance technology have become an important component in today's mid-range computing and communications systems. Through the dedicated effort of many scientists and engineers, HPCC has succeeded in laying a foundation for future growth.

Historically, high performance computing was a specialized market segment within the computer industry, serving the specialized needs of science, engineering, and national defense. High performance supercomputers were based on unique architectures and technologies, optimized to the requirements of these compute-intensive applications, and expensive relative to mainstream computers. However, over the last few years, the use of high performance computing has undergone a major transition from purely compute-intensive applications to include data- and communications-intensive ones. As the focus broadened, the description "high performance computing" was broadened to "high-end computing." In addition, with the advent of powerful microprocessors used in workstations and servers, a large portion of the high-end computing market transitioned from supercomputers to symmetric multiprocessors (SMP) and parallel systems. These systems, based on commodity parts, are available at a fraction of the cost of earlier supercomputer systems. However, highly parallel systems (100s to 1000s of processors) with the potential of ever increasing performance into the teraops range and beyond have not met all expectations.

Thus, high-end computing can be viewed as three distinct and highly inter-related markets, each with its own dynamics and issues:

1. The broader data-intensive, and communications-intensive market, with applications like data mining, web serving, digital libraries, and transaction processing. This market is doing very well, and growing very fast.

2. The scalable, microprocessor-based compute-intensive market. This market is doing quite well at the mid-range of the market, with SMP based systems and moderate size parallel systems. However, the high end of this market, that highly parallel systems are expected to fill, remains in the research/experimental stage because of the lack of adequate software technology, application development tools and, ultimately, a paucity of applications.

3. The legacy, vector-architecture-based sector is a market with hundreds of installed systems. This is a shrinking market, primarily because most new applications are being developed for

the more modern and economical microprocessor-based systems. Thus, the majority of the market for such vector systems is with older applications that have not as yet been moved over to SMP/parallel systems. The aforementioned lack of good software technology and tools make it very difficult either to move or rewrite the applications for SMP/parallel systems.

Research in high-end computing has had far-reaching benefits to society. Many of the present uses of high-end computing are documented in previous reports.[234] They include:

■ designing new cancer fighting and anti-viral drugs;

■ understanding the causes and sources of air, water and ground pollution, and devising solutions to these problems;

■ forecasting local weather and predicting long-range climate changes;

■ designing safer, fuel-efficient vehicles;

■ ensuring the safety and effectiveness of the Nation's nuclear stockpile;

■ designing new aircraft, such as the Boeing 777; and

■ simulating the effects of attacks on weapons systems, such as the New Attack Submarine.

3.3.1 Findings

Finding: High-end computing is essential for science and engineering research.

The successes of the HPCC program have led to widespread use of computational simulation and modeling as a means to understand natural phenomena and to explore and optimize engineering designs. Over the next few decades, computation will become even more essential to the Nation's science and engineering endeavors. Some of the research that uses high-end computing is done under the auspices

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[2] Brooks, Jr., Frederick P. and Ivan E. Sutherland , co-chairs, "Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure," prepared by Committee to Study High Performance Computing and Communications: Status of a Major Initiative, National Academy Press, 1995.

[3] Lax, Peter D., [chairman], Report of the Panel on Large Scale Computing in Science and Engineering Under the sponsorship of Department of Defense (DOD) and National Science Foundation (NSF), in cooperation with Department of Energy (DoE) and National Aeronautics and Space Administration (NASA).

[4] Department of Defense, "National Security High End Computing Integrated Process Team for National Security High Performance Computing," briefing 1997.

of mission agencies such as the Department of Energy (DoE), but a significant portion is also sponsored by the National Science Foundation (NSF). Both for the sake of fundamental science research, and in order to bring the benefits of that research to the applications that can exploit it, the civilian science research community needs access to systems at the leading edge of capability, comparable in power to those available to the mission agencies. Furthermore, if the benefits of high-end computing are to continue to accrue in the scientific community, it is important to ensure that there are enough computer and computational scientists to collaborate in making leading-edge computation an effective tool for scientific research.

Finding: High-end computing is an enabling element of the United States national security program.

Government customers account for at least half the market for supercomputer systems, with national security programs historically driving the market. These programs are very important to the Nation. Such government organizations face the challenge of converting their applications to new high-end architectures without disrupting their missions. This transition has proved to be technically difficult. The DoD HPC Modernization Program, Department of Energy (DoE) Accelerated Strategic Computing Initiative, and National Security Agency are examples of government uses of high-end computing.

Through the DoD HPC Modernization Program, the Office of the Secretary of Defense is investing more than one billion dollars over five years in high-end computing to provide the United States military with a technological advantage. This program will provide advanced hardware, computing tools and training to DoD researchers using the latest technology to aid their mission in support of the warfighter. The incorporation of high-end computing will allow the United States to maintain its technological supremacy in weapons systems design into the foreseeable future, while decreasing the total life-cycle costs of fielding new warfighting support systems.

The Department of Energy (DoE) Accelerated Strategic Computing Initiative (ASCI) program is critical to the Stockpile Stewardship Program. ASCI is designed to assist in ensuring the safety, reliability, and performance of the United States nuclear stockpile in the absence of underground testing. The computer technology and products developed by the ASCI program will be applied to a broad spectrum of national needs, bringing economic and scientific benefits to the United States in the fields of environmental studies, biology, drug design, automobile and aircraft development, consumer product safety, and information management and access.

The National Security Agency (NSA) has traditionally influenced and been a very early and sophisticated user of the highest performance commercial computer, storage, and networking systems. In its mission to protect U.S. information systems and produce foreign intelligence information, the NSA has stimulated both industry and academia with some of the most challenging problems in the Nation. Research is directed to the discovery and application of methods seeking order of magnitude improvement for deriving intelligence from mathematical and signal processing problems. Activities range from invention and prototyping of new concepts, to improvement in the ability to use leading edge commercial products. NSA sponsors the Center for Computing Sciences, a division of the Institute for Defense Analyses, to do most of this research.

Finding: New applications of high-end computing are ripe for exploration

In addition to advancing the long-term research agenda in traditional high performance computing, the Committee believes that there is a strong need to develop uses of high-end computing where it has not been exploited in the past. This is particularly important, since it is vital to attract computer, software, and application vendors to support a healthy high-end computing marketplace. Today the high-end computing market is a shrinking fraction of the overall IT industry. Among the areas in which high-end computing could have enormous advantages are:

- "intelligent" systems—using sophisticated data mining algorithms against very large data bases to make expert decisions in a variety of application areas, from health care to market research;

- design—using Computer Assisted Design and Engineering technologies in the many, more mundane, but far more broadly applied sectors such as fashion and architecture rather than just in extremely important but rarefied fields like aircraft design and nuclear weapons stewardship;

- transportation—managing route optimization and fuel efficiency for aircraft more effectively, at a savings of billions of dollars per year;

- crisis management—simulation of crisis scenarios, particularly weather and groundwater flow, is critical to the management of emerging crises as well as to conducting training and preparedness exercises; and

■ infrastructure support—managing the large-scale networks that are increasingly essential to the Nation's economy and government.

Finding: Suppliers of high-end systems suffer from unusual market pressures.

Despite the economic and societal benefits of solving problems like those described above, the market for high-end computing systems is mixed. The low- and mid-range parts of the high-end market (workstations and servers) are doing well financially, however the highest end, sometimes referred to as "supercomputing" to reflect its origins, has not been growing and has sales of less than $2 billion per year. This part of the market, historically dominated by U.S. vendors, has gone through an intense period of consolidation in the past several years leaving only SGI (together with its Cray subsidiary), IBM, Sun Microsystems, and HP as significant U.S. participants, and no U.S. company remains with its primary focus on technical, high performance computing.

At the same time, foreign competitors have enlarged their efforts to capture the very high-end market, which creates a potential reliance on non-U.S. vendors for future high-end systems. The Committee believes that this trend will continue unless the U.S. invests in research and development programs in cooperation with industry and academia to increase U.S. leadership.

3.3.2 Recommendations

In high-end computing as in other parts of information technology we need more fundamental research—the kind of groundbreaking, high-risk research that will provide the ideas and methods for new disciplinary paradigms a decade or more in the future. The greatest needs are exploring innovative architectures and devices, improving systems and algorithm-level software support at the high end, and making it possible for the academic research community and the Federal Government to conduct essential research and development on computers of the highest possible performance. Research on the hardware, software, and architecture can be effectively driven by an initiative to reach a petaflops/petaops sustained performance by the year 2010. To have the most impact, research on and access to high-end computing systems should be coordinated across all the Federal agencies through the High End Computing and Computation (HECC), a multi-agency coordinated part of the federal computing, information, and communications, process.

Recommendation: Fund Research into Innovative Computing Technologies and Architectures.

There is substantive evidence that current scalable parallel architectures are not well suited for a number of important applications, especially those where the computations are highly irregular or those where huge quantities of data must be transferred from memory to support the calculation. To address these limitations, the Committee recommends expanding research and development funding for new computer architectures. In particular, substantive research is needed on the design of memory hierarchies that reduce or hide access latencies while delivering memory bandwidths required by today's applications and those that will develop in the future. In addition, the Committee recommends funding research into promising new technologies such as optical, quantum and DNA computing. Ultimately silicon chip technology will run up against the laws of physics. When this will happen is not known exactly, but as devices approach the size of molecules, scientists will encounter a very different set of problems attempting to continue to make computing components and hence computers faster. The Committee feels that we must begin to invest now in these new technologies to ensure that we will have continuing improvements in computing capability well into the 21st century.

Recommendation: Fund R&D on software for improving the performance of high-end computing.

The Committee recommends substantial investments in software to improve the performance and efficiency of high-end computers. The software investments fall into two categories. The first is system software, where investments in languages, compilers, runtime libraries, operating systems, file systems, I/O drivers, debuggers, programming interfaces, performance tuning tools, etc. will lead to improved efficiency and performance, while making high-end systems usable by a much larger user community. The second area is algorithm development, where continuing investment is needed to ensure the efficient use of leading-edge machines. Efforts in software and algorithms can make it possible to exploit parallelism effectively and to use memory hierarchies efficiently. These efforts are essential not only to increase usability, but also to facilitate the transition of applications, including those essential to national security and to new computer architectures.

Recommendation: Drive high-end computing research by trying to attain a sustained petaops/petaflops on real applications by 2010 through a balance of hardware and software strategies.

38

43

The Committee has reviewed the HECC program's proposed petaflop activity. The preliminary studies sponsored by that program have determined that substantive technological advances will be needed to achieve the desired performance levels by 2010. We believe that the goal of building systems capable of achieving sustained performance on important applications at the petaops or petaflops level can be an effective way to drive research on the hardware technologies, new architectures, software systems, and algorithms that will be needed to make such systems possible. We, therefore, recommend that funding for this program be increased to ensure that the necessary technological advances—in algorithms, systems software, application-level software components, and hardware—are achieved. It is essential that the goal of sustained petaops/petaflops performance be understood as a technology driver and not a goal unto itself. It is possible, but unlikely, that sustained, real-world petaops/petaflops performance could be reached by faster hardware technology and increased hardware parallelism alone, but these sustained performance levels are almost certain to require a tightly-coupled, well-balanced effort on both software and hardware. It would be counterproductive to produce a computer system capable of petaops-level performance without the software and algorithms needed to make it usable for the full range of high-end applications. An appropriate program will, for example, accommodate a technical comparison and evaluation of current architectures with promising new ones such as those based on processor-in-memory components. It should also ensure that the software challenges of programming computers with tens or hundreds of thousands of processors and deep memory hierarchies are adequately addressed.

Recommendation: Fund the acquisition of the most powerful high-end computing systems to support science and engineering research.

Increasingly, high-end computing will be critical to science and engineering research. If the United States is to continue as the world technological leader, its scientists and engineers must have access to the most powerful computers available. Therefore, the Committee recommends that the Federal government continue to provide these systems to the research community through major centers, for example, but not limited to, the NSF Partnerships in Advanced Computational Infrastructure (PACI), the DoE ASCI Centers, and the DoD HPC Modernization Shared Resource Centers. In addition, efforts should be made to expand the use of high-end computing to support information technology research. For example, the simulation of proposed petaflops/petaops architectures will be essential to the development of software for those systems, yet such simulators cannot even run simple computational kernels without using

computers of the highest possible performance. The Committee, therefore, recommends funding additional high-end systems to support the Research Expeditions to the 21st Century described in Section 4.2.2. These high-end systems will enable truly innovative research and thereby assist in developing a cadre of researchers to exploit high-end computing in the next century. These high-end systems will also create an environment for new applications and increased demand for the critical, domestic high-end computing industry.

Recommendation: Expand the Federal High End Computing and Computation (HECC) program to include all of the major elements of the government's investment in high-end computing.

The Committee recommends that all of the major investments of the Federal Government in high-end computing be included in the High End Computing and Computation (HECC) program. Currently large investments in high-end computing such as the Department of Energy's Accelerated Strategic Computing Initiative (ASCI) and the Department of Defense's High Performance Computing Modernization Program (HPCMP) are not included. Thus, these programs are generally not included in the Federal Government's attempt to coordinate high-end computing across agencies. Exclusion of such big investments makes it very difficult to coordinate and plan R&D activities for high-end computing.

3.4 Socio-Economic and Workforce Impacts

3.4.1 Socio-Economic Impacts

As more and more advances in high technology are introduced into our society, it has become increasingly important for our national social and economic well-being that we understand the transformations and potential dislocations affected by technology adoption and diffusion. The ELSI (Ethical, Legal, Social Implications) Research Program of the National Human Genome Research Institute establishes a precedent for conducting this type of research within the framework of a broad-based, large-scale Federal R&D program. The Federal R&D program for IT recommended in this report is similarly broad-based and large-scale, both in program scope and in its promise for continuing to transform our society and economy. Thus, if as a Nation we are to fully capture the promise of the new technologies we develop, it is important to include within that program a research agenda to address the social and economic implications of IT adoption and diffusion.

There are several key drivers for establishing a socio-economic research agenda for information technology:

- The impact of IT on our economy, society, culture and political systems is seemingly pervasive. Although many

speculate on its impact, much of this speculation is occurring in the absence of solid, empirical data.

■ A workforce literate in information technology will be critical for ensuring that our Nation is prepared to meet the challenges and opportunities of the Information Age. To create an IT-literate workforce, we must ensure that opportunities are extended to all Americans to increase overall IT literacy and to access IT tools for learning, research, communications and collaborations. We must also enhance our national capacity to sustain R&D in computing and communications by ensuring greater participation in IT research. Full participation requires access to high-bandwidth connectivity opportunities for universities and research institutions that traditionally have been underrepresented in research partnerships, including institutions in EPSCoR states, small institutions, predominantly ethnic institutions, and those in geographically dispersed locations.

■ Information technology can be used as a vehicle to help eliminate social and economic inequities. IT tools and applications can provide opportunities that transcend barriers of race, gender, disability, age, income, and location. The enabling quality of the technology, in addition to the cultural values cultivated through its most well-known application, the Internet, carry a democratizing potential that already has transformed our social interactions and economic opportunities, both at home and abroad.

■ The use of IT, in particular the growing popularity of the Internet, and the emergence of global economic commerce has introduced a series of important and complex policy issues, such as privacy, intellectual property rights, the emergence of information "haves" and "have nots," and the impact of state and national regulation. For the most part, neither these issues nor the resulting debates have been properly informed by research. Social scientists may be able to make important contributions to these ongoing debates by conducting empirical research on the impact of IT and the social policy necessary in the next Millennium. Such research also can help IT researchers identify potential technical solutions for addressing these policy issues (e.g. new metadata tagging standards and micropayment technologies for managing intellectual property).

■ Insights derived from social science research may be able to contribute to the actual design of information systems. The design of groupware, for example, should be driven by

46

research on how groups of people share information and make decisions.

■ Many of the barriers to realizing the benefits of IT are not technical, but rather occur when social, political, or legal issues arise as attempts are made to deploy and adopt the IT and its applications. For example, deployment of telemedicine is being slowed because of the need for state-by-state licensing of doctors. The use of geographical information systems (GIS) is hampered by the difficulty of sharing this data across organizational boundaries. Widespread use of electronic commerce will require mechanisms for creating trust between parties in an online environment. Social science research could shed light on these barriers and suggest possible solutions.

3.4.2 Socio-Economic Recommendations

Recommendation: Expand Federal research on the social and economic impacts of information technology diffusion and adoption.

Recommended research topics include:

1. How to mitigate potentially negative socio-economic impacts associated with IT deployment (e.g. IT impact on: social interactions; racial, gender, and/or class inequities; labor; privacy; abridgement of citizen's rights; ethics in information management and dissemination.)

2. The mechanisms for expanding and strengthening our national IT research expertise, including how best to ensure that universities and research institutions are not subjected to undue restrictions on access to high-bandwidth connectivity and opportunity for participation in IT R&D due to size, type or geographic location.

3. The scope for implementing technical solutions as an alternative to government regulation to address issues raised by global electronic commerce, including but not limited to intellectual property protection, content regulation, privacy, and security.

4. The impact of social, economic, political, and legal barriers on technology development and deployment.

5. The circumstances and degrees to which industry self-regulation can be effective in solving complex social issues such as consumer privacy.

47

6. The effect of economic, regulatory, and market factors on the propensity of telecommunications companies to continue to invest in the national information infrastructure, including broadband networks.

7. The measures that will appropriately capture the impacts on productivity due to private and public sector investments in IT.

8. The impact of the growing role of electronic commerce in our economy and the resulting effects on economic strength, growth, and U.S. competitiveness.

9. The impact of the information economy on important societal institutions, such as education, health care, and government.

Recommendation: Expand Federal initiatives and government/university/industry partnerships to increase IT literacy, access and research capabilities.

In his remarks at the MIT commencement ceremony on June 5, 1998, the President reiterated his vision of limitless possibilities for all Americans brought about by the very technical advances that we are recommending in this document. One of the challenges before the Nation in supporting that vision is to overcome the current inequities and geographic disparities in access to and use of IT applications. In an increasingly competitive global economy, our Nation cannot afford to squander our human resources by providing those opportunities only to those Americans who are favored by geographic or economic circumstance. Access to and use of IT, particularly in educational settings (K-12 as well as higher education), is a prerequisite to building the skills base that will allow our citizens to function productively in the information society of the next century. It is also a critical stepping stone for instilling interest and developing the skills of the budding IT researchers who will be essential to sustaining our national research capabilities. Therefore it is essential that, in establishing the partnerships to implement the research agenda recommended in this report, the Federal government increase its efforts through programs such as EPSCoR or other appropriate mechanisms or programs (potentially to be tied to specific research topics) to provide opportunities for developing IT literacy, access and research capabilities. It is also essential that the Federal government expand opportunities for IT literacy and access as it addresses issues related to workforce skills and development. Specific recommendations are provided in the section below.

3.4.3 IT Workforce Issues   The Committee believes it is important to separately highlight workforce issues, as it sees the Nation facing an impending crisis in

preparing American workers to be productive in an economy that is increasingly dependent on IT. Although the use of computers in education is increasing at all levels, and computer literacy is increasing dramatically across America, too few Americans are entering or receiving necessary re-training in the computing, information, and communications professions. Market forces alone will not correct the problem. The Federal government must do more to help educate and re-train people in these crucial fields and to bolster the academic pipeline — from elementary school to post-graduate study.

The tremendous commercial success of computer, information and communications technologies paradoxically threatens to erode the very foundation on which it rests. Industry demand for R&D professionals is exceeding supply to such a great extent that the Nation's research laboratories and educational centers are hard-pressed in their efforts to grow their intellectual capital base, yet education and training are essential for the future growth of information industry.

The academic pipeline and re-training efforts are deficient. Since 1991 the rate of growth in computer science and electrical engineering doctorates has decreased. The annual number of doctorates granted in computer science, in particular, not only stagnated during the 1990's, but is down about 10 percent from the peak in 1991-92. The short-term outlook shows no immediate improvement. At a time when we should encourage students to continue graduate study, electrical engineering and computer science majors are among the least likely to pursue a Ph.D. In comparison to the biological and health sciences, electrical engineering and computer science turn out about half as many doctorates. Computer science and electrical engineering together account for only about 5 out of every 100 master's degrees, and 6 out of 100 doctorates granted each year. In addition, an increasing percentage of these graduate students are foreign students.

The data should surprise no one. A lack of adequate preparation for American students at the secondary education level is certainly one factor contributing to the decline. The poor performance of our twelfth graders in the Third International Math and Science Survey is just one indication of the problem. Both computer science and electrical engineering are among the most rigorous and challenging courses of academic study, and students need a strong foundation in mathematics.

The current imbalance between U.S. demand and supply for skilled IT workers is another factor that further exacerbates this problem. The supply of incumbent and re-trained workers is not sufficient to

meet the information technology industry's robust demand for skilled workers. In this tight labor market, companies seize upon opportunities to hire talented computer science and engineering majors who might otherwise pursue graduate careers. Another labor pool available to information technology and other high technology companies are skilled foreign workers, who are recruited from abroad or from American graduate schools. The size of this labor pool is dictated by the annual cap on the number of visas for temporary foreign "specialty" workers under the government's H-1B program. A short-term increase in the H-1B visa cap can provide a partial remedy for the industry's immediate labor problems.

3.4.4 IT Workforce Recommendations

Recommendation: Increase research funding to help address the shortage of high-technology workers.

To increase the number of computer science bachelor's graduates significantly, we need more faculty members. To increase faculty sizes, we need to produce more Ph.D. computer scientists. We cannot do that without increasing the number of students entering graduate school or recruiting a larger percentage of those students into academia when they finish. Although salary is a major factor in a student's decision not to go to graduate school, an equally important factor is the perception that universities are no longer the place where the most exciting work is being done. Substantial increases in funding for long-term research would change that.

Recommendation: Develop new educational programs to re-train information technology workers whose skills have become outdated.

While investment in long-term research in universities will help to ensure an adequate supply of information technology professionals for careers in academia, industry and the public sector, this approach cannot by itself solve the current serious shortage of skilled workers.

Recommendation: Encourage increased participation by women and minorities.

To remain competitive in a global economy, we need to ensure that every American emerges from school with the general and specific skills needed to prosper in an information rich society. Current studies show that women and minorities are vastly underrepresented in both educational and workplace settings which require the development and/or use of information technology skills. Our Nation will not prosper if we do not invest in developing all our human resources.

Recommendation: Increase the annual cap on H-1B visas as a short-term remedy to address the shortage of skilled IT workers.

Congress is considering a bill which would raise the annual cap on the number visas for temporary foreign "specialty" workers under the H-1B program. Increasing the cap would allow IT companies to recruit more foreign graduates of American universities. Certainly the long-term solution is to make information technology careers more attractive to American students and to provide adequate training for existing IT workers. But in the short term, increasing the limit on H-1B visas is a partial remedy that should be part of a balanced plan to address the shortage of skilled IT workers.

4. New Federal Research Initiatives: Support and Implementation

4.1 Findings

To achieve the goal of reinvigorating long-term, high-risk research in information technology, Federal funding agencies must consider not only funding levels and research agendas, but also the modes of support that can best accomplish the goals. As a consequence of changes in funding levels and funding sources over the years, some of our most fruitful modes of support have been lost.

Finding: The Federal IT R&D funding profile is incomplete.

The current funding portfolio is not properly balanced. It is deficient in the support of multiple-investigator projects focused on research problems with multiple-year timeframes. Funding for projects of longer duration and larger scope is critical to the Federal research program. Projects of larger scope allow for multiple-investigator, interdisciplinary collaboration, intramural research in academia and Federal research institutes, and joint industry-Government-academia experiments or proofs of concept. Projects of longer duration allow exploration of research problems with multiple-year horizons, which may lead to unexpected and significant discoveries.

It is important that Federal investments include a range of complementary funding modes, including classical single principal investigator (PI) research, multiple-investigator projects within and across disciplines, and multiple-institution/multiple-year efforts. Such diversity in funding approaches and tactics is important. It provides complementary modes for research, ensuring a broad perspective in addressing problems, thus increasing opportunities for discoveries.

Furthermore, because effective research in computer science involves collaborations of all sorts—with other computer scientists, with researchers in other disciplines and at other institutions, with industry, and with the community—the modes of support should encourage these collaborations, without turning them into strict requirements. Flexibility is needed to organize research projects in the best ways possible to achieve the goal of technological innovation.

New Federal Research Initiatives:

4.2 Recommendations for new and diverse modes of funding

Although single-investigator projects can lay the technological foundations for progress, they do not provide for large-scale, sustained, and integrated exploratory research. The Committee believes that a richer portfolio of funding modes is needed. There should be expanded emphasis on support for multiple-investigator teams working on a single integrated project over a number of years. This model has been successfully used by DARPA for many years. In addition, to foster research that can have truly dramatic impacts, the Committee recommends the creation of two types of center-sized activities. "Expeditions into the 21st Century" will involve large teams of researchers in explorations of future information technologies and their impact on society. "Enabling Technology Centers" will conduct research on the application of information technology to particular problems of national importance.

4.2.1 Recommendation

Diversify the modes of research support to foster projects of broader scope and longer duration.

The Committee believes that targeted research investments in software, scalable information infrastructure, and high-end computing alone will be insufficient to maintain U.S. economic leadership and meet defense and other national needs. Such focused investments, while necessary to maintain leadership in component technologies, do not address the larger effects of the emerging information age.

To be truly effective, increased research investments must foster exciting new visions for the future and support investigations of these visions. In information technology research, the most successful way to build vision has been through multi-investigator teams working on an integrated project over some number of years. Such teams can range from a few researchers to many, but to be successful, they must have the time and resources to effectively explore their ideas.

This approach was used with great success by DARPA during the 1970's and 1980's, when teams of computer science researchers were encouraged to imagine and explore dramatically different futures. These teams were given enough resources and time so they could concentrate on the problem rather than worry about their next proposal. The results were dramatic advances in artificial intelligence, speech recognition, robotics, chip design, high-performance computing, machine vision, and virtual reality. It is this spirit that the Committee would like to see reborn and replicated across all Federal funding programs for information technology. DARPA's role as a funder of innovative, high risk initiatives in information technology should be restored as part of a balanced R&D program.

48

4.2.2 Recommendation

Fund virtual centers for Expeditions into the 21st Century.

"Expeditions into the 21st Century" will be virtual centers that bring together scientists, engineers, and computer scientists from academia, government, and industry to "live in the technological future." The mission of these expeditions will be to report back to the Nation what could be accomplished by using technologies that are quantitatively and qualitatively more powerful than those available today. In essence, these centers will create "time machines" to enable the early exploration of technologies that would otherwise be beyond reach for many years. Just as the Lewis and Clark expedition opened up our Nation and led to unanticipated expansion and economic growth, the ideas pursued by information technology expeditions could lead to unexpected results and nourish the industry of the future, creating jobs and benefits for the entire Nation.

There are a number of precedents for this "living in the future" approach. In the private sector one of the most famous examples is the Xerox Palo Alto Research Center (PARC), where researchers created an experimental network of computers for use by individuals. This effort pioneered many of the revolutionary technologies that led to today's personal computers, including graphical user interfaces, pointing devices, laser printing, distributed file systems, and WYSIWYG word processing. In the university community, the Massachusetts Institute of Technology (MIT) Media Lab has been conducting similar explorations. Finally there is the example of ARPAnet, which evolved into today's Internet.

The Committee recommends funding several Expeditions, each with a different focus. The focus may be on either a discipline-based theme, such as bioinformatics or multi-scale engineering, or on an infrastructure-based theme, such as distributed databases or tele-immersion. To establish a context, each Expedition should be based on assumptions not true today, for example, ubiquitous computing or a vast amount of simulation (à la Gelernter's Mirror Worlds). Each center need not be limited to a single such assumption, but an Expedition should invest sufficient resources to make exploration of its assumption areas, those parts of the map of the future, possible.

Expedition Center Functions

Each Expedition would be required to carry out several activities, including:

1. Technology testbeds. Centers would be expected to establish testbeds in which the future technologies that are the focus of their activities could be effectively explored in a realistic setting.

The computing environment established by Xerox PARC is a good example of such a testbed.

2. Economic and societal impact studies. Expeditions should include research on the impact of future technology on society. Such studies should involve researchers from disciplines other than computer science.

3. Education. Each center should have an extensive educational program to inspire students of all backgrounds to think about the long-term technological future and its implications.

4. Outreach. Expeditions should reach out to the research community, to industry, and to the public. The purpose of these programs is to accelerate the realization of the center's vision in the form of knowledge and products. Outreach to the research community should include open meetings where the results and impact of center activities are publicly presented.

Expedition Selection Criteria

Criteria for selecting proposed expeditions for funding include:

- Elucidation of a clear and exciting vision for the future.

- Novelty of the technological area of exploration.

- Identification of significant Computer Science and Engineering (CS&E) research challenges

- A coherent plan for carrying out and managing the proposed activities.

Expedition Funding and Management

The Committee recommends creation of up five Expeditions, to be selected via a competition to establish a core activity, with a standard process to allow additional researchers to participate. Competitions should be held at regular intervals, e.g., every three years, to ensure a continual flow of new ideas. It is expected that these "virtual centers" will include investigators from many research institutions. Each center would receive an initial five-year funding agreement, renewable for five years. The full term of an Expedition would be ten years. To encourage truly aggressive efforts, very high annual funding levels should be possible, say up to $40 million per center.

4.2.3 Recommendation

Establish a program of Enabling Technology Centers.

The Committee recommends establishment of centers of excellence in computer science and engineering applied to particular applications of information and communications technology. These Enabling Technology Centers (ETCs), located at university and/or Federal research institutes, will provide an integrated environment for academia, industry, and Government to focus on the application of next-generation IT to important national problems. There is a wide variety of applications domains where information and communications technologies could make a difference, including: computational science and engineering; health care; delivery of Government services/Digital Government; crisis management; environmental monitoring; life-long learning; law enforcement and public safety; arts, culture, and the humanities; intelligent transportation systems; improving the quality of life for persons with disabilities; and distributed work (e.g. telecommuting, collaboration by geographically distributed teams).

Enabling Technology Center Functions

The ETCs will be focused on applied technology and development. Researchers at the centers will conduct R&D in CS&E to support the chosen application domain, develop new curricula for students and mid-career professionals, participate in testbeds, and identify barriers to more widespread adoption of IT in a particular applications domain.

These centers should perform several functions, including:

1. Research and development on applications and application development environments. Researchers will develop prototype applications that will rapidly become usable on commodity products and services.

2. Education and training. Researchers will develop educational programs and curricula based on the intersection between CS&E and a particular applications domain. The programs should be aimed at undergraduates, graduates, or mid-career professionals and be delivered using both traditional classroom-based instruction and distance learning. The 1992 National Research Council report, *Computing the Future,*[5] contains a number of suggestions for how this might be done, including "developing a joint program between CS&E and a discipline X that uses computation heavily."

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[5] Hartmanis, Juris, and Lin, Herbert, eds., *Computing the Future: A Broader Agenda for Computer Science and Engineering.* National Academy Press, 1992.

3. Testbeds. Researchers will participate in the experimental deployment of information systems "in the field." *Computing and Communications in the Extreme*[6] makes the case for the value of testbeds:

■ They can serve as a demanding implementation environment for new technologies and sources of feedback to identify and refine research objectives. Such testing is particularly important ... in order to verify theoretical concepts about the scalability of system characteristics, interoperability with other systems, and usability by people in realistic situations—all of which are difficult to predict in the laboratory. Discussions with experts in a number of application domains revealed that although support of people—both as users and as integral parts of the system design—is of primary importance, this need gets too little emphasis in system design.

4. Research on factors that are inhibiting or preventing the deployment of IT in a particular domain. Researchers may discover that the use of IT in particular application domains is being slowed by legal and regulatory barriers, lack of end-user training, the absence of compelling cost-benefit analysis, a lack of technical standards or other mechanisms for interoperability, etc.

5. Community-building. The centers could help build communities of researchers, companies, Government officials, users, and other stakeholders by convening conferences and workshops, developing research agendas, and supporting intellectual infrastructure such as e-print archives, collaboratories, databases, and case studies of successful and unsuccessful uses of IT.

Enabling Technology Center funding and management

The Committee recommends that funding for the ETCs be shared between mission-oriented agencies with an interest in a particular applications domain and an agency with a broad mandate to support CS&E research (e.g. the National Science Foundation).

Awards need to be of sufficient duration and size to support a critical mass of researchers interested in a particular applications domain. The Committee recommends each center be funded on the National Science Foundation Science and Technology Center funding model, under which each center would receive a five-year cooperative

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[6] National Research Council, *Computing and Communications in the Extreme: Research for Crisis Management and Other Applications*, National Academy Press, 1996.

agreement stipulating that formal review be conducted in the third year for renewal of support. Centers passing the third year review would receive a new five-year cooperative agreement requiring a formal review the sixth year. The full term of an ETC would be 10 years. Annual funding of up to $10M per center is recommended, with up to 15 centers simultaneously in operation. Competitions would be held every three years.

5. New Federal Research Initiatives: Creating an Effective Management Structure

Given the importance of information technology to the Nation's future, it is critical that the Federal investment in R&D in this area be well managed. Furthermore, if we are going to invest substantially increased funding in an attempt to stimulate exciting new activities in information technology, we must establish management structures to ensure that it will be used effectively and for the desired purpose. An effective management structure can ensure thorough oversight of all key areas in the Federal R&D portfolio and can help the Administration articulate R&D priorities and assure Congress that it is meeting its goals.

Currently, funding for information technology R&D comes from several different agencies, with no single agency having information technology as its primary responsibility. This system has worked surprisingly well in the past. However, there is the danger that, as the national information technology enterprise grows larger, its prominence in the Federal funding portfolio will not keep pace with its importance to the economy, due to the natural tendency of each agency to concentrate on its primary mission. Furthermore, by focusing on their individual missions, agencies tend to drift toward an emphasis on short-term research, particularly in the face of budgetary constraints. This is one of the principal reasons for the shift of funding away from fundamental research, particularly in the mission agencies.

5.1 Managing Long-term Research

Given that increasing fundamental long-term research is one of the principal goals of this report, the Committee believes that we need to have a principal agency upon which to focus that activity. This agency could serve as the "lead agency" for coordinating information technology research, helping to define and prioritize activities in the area. One strategy would be to create an independent Federal agency, with information technology as its only focus. However, we recognize that with today's desire for small government, a new agency is not practical. Thus, this function must fall to an existing agency. Because the mission agencies must put the accomplishment of their primary mission first, they are not well suited to this function.

Thus the only currently feasible candidate for this role is the National Science Foundation (NSF).

At first glance, NSF seems ideal, given that support of basic research is its primary mission. However, to successfully carry out the program of research proposed in this document, information technology will need to be elevated within NSF. NSF will need to support a portfolio of modes of research that differs from the current mix of mostly single-investigator research grants together with a small number of centers. For example, multi-investigator projects of longer duration (5-7 years of funding) are needed in order to carry out experimental research agendas (whether or not such grants are available in other parts of the Foundation). Some of these projects will include applied research and technology transfer. Some projects will be supported in response to topic-specific Requests for Proposals in order to support a DARPA-like concentration of effort on compelling research areas. The portfolio must successfully meld science investigations with technology exploration. In addition, there needs to be significantly more Information Technology representation on the National Science Board than exists now.

5.1.1 Recommendation

Designate NSF as the lead Federal agency to coordinate information technology research.

Designate the NSF to serve as the lead organization for coordinating information technology research within the Federal Government. This may require institutional innovations internal to the NSF to ensure that NSF is responsible for defining and coordinating a broad range of modes of research support, such as centers of diverse sizes and multiple-investigator projects with longer terms. Roughly half of the proposed budget increases for information technology should go to NSF with the rest allocated to other research support agencies. The majority of the NSF increase should go to the new modes of funding; the rest should go to the traditional style programs within Computer and Information Science and Engineering, expanded as appropriate to projects of larger size and longer duration.

5.2 Coordinating Long-term Research

Another problem with the present management structure is the difficulty of getting a clear and complete picture of the total Federal investment in information technology. Given that approximately half of the proposed budget increases would go to agencies other than NSF, the overall information technology endeavor must be properly coordinated. For that to happen, all R&D programs must fall within the coordination program. (For example, we see no reason why the DoE ASCI program has been outside the current crosscuts.) An expansion of the coordination mechanism used for HPCC and NGI to the entire IT endeavor is an appropriate vehicle.

Clearly, the coordination in information technology must encompass major equipment investments in R&D as well as investments in people, supplies, and the like. For instance, high-end computing acquisitions are a necessary part of a coordinated program.

5.2.1 Recommendation

Expand the current coordination mechanisms already in place.

Expand the current coordination mechanisms used for HPCC and NGI—a Federal coordination committee with staff from a national coordination office and topical working groups, with oversight by a Presidential advisory committee—to the entire information technology research endeavor. The coordinating committee should consist of agency representatives who have budgetary authority and should establish objectives for research programs and review them to ensure that they are meeting those objectives. In addition, it should ensure that the overall Federal program is well planned and has good coverage of important topics.

5.3 Annual Review

Finally, in order to ensure that the modes of research proposed in Section 4 are implemented, the coordination committee should review information technology research programs annually to ensure that they maintain the proper balance in funding modes and the right balance between long-term research and short-term needs.

5.3.1 Recommendation

Establish a comprehensive annual review of research programs.

The coordination committee, with advice from the advisory committee, should conduct an annual review of research programs to ensure that they are achieving the goals set out for them. In particular, it should ensure that the modes of support proposed for the program—centers, multiple-investigator interdisciplinary projects, and testbeds, along with a renewed emphasis on long-term research— are not being compromised and that these modes of research support are meeting the goals set out for them.

6. Conclusion

In both the public and private sectors today, U.S. investments in information technology R&D, particularly fundamental research, have stagnated. American businesses, in an ever-shrinking and more highly competitive world, have devoted fewer and fewer precious resources to long-term R&D and internal long-range laboratory research, directing their efforts instead to reducing costs and getting new products into the pipeline today at the expense of future development. U.S. Government research in high end computing and computation—so crucial to keeping our military edge in the competitive era of the Cold War—seems to have collapsed along with the Berlin Wall. The once robust technological edge the U.S. has enjoyed over the rest of the world is built on an increasingly fragile technological substructure. To keep its competitive edge and address problems of critical importance to its people, the United States must rededicate itself to cutting edge high-technology research and development or risk being passed by nations with a clearer plan and a stronger vision for the future. This is a risk the United States cannot afford to take.

The initiatives presented in this report reinforce the recommendations made in the Brooks-Sutherland report *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*. Our proposed initiatives take a major step toward restoring the critical importance of a comprehensive, long-term Federal research program focused on high performance computing and communications and information technology. The time to act is now. The Federal government has the unique opportunity to support the critical research needs driving this key, rapidly changing industry that is responsible for one third of this country's economic expansion. The Brooks-Sutherland report stated this well:

> Very few companies are able to invest for a payoff that is 10 years away. Moreover, many advances are broad in their applicability and complex enough to take several engineering iterations to get right, and so the key insights become "public" and a single company cannot recoup the research investment. Public investment in research that creates a reservoir of new ideas and trained people is repaid many

times over by jobs and taxes in the information industry, more innovation and productivity in other industries, and improvements in the daily lives of citizens. This investment is essential to maintain U.S. competitiveness.[7]

This Committee strongly recommends that the Federal government recommit itself to the kind of leading-edge, visionary research necessary for transforming the lives of our citizens in ways not thought possible just thirty years ago. The Committee also stresses the need to upgrade the knowledge base and skills of the nation's workforce, so that its citizens will be prepared for the technological challenges of the new century, and to give all Americans the opportunity to participate in the information age.

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[7] Brooks and Sutherland, 1995:23.
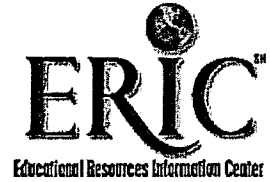
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